

NJDOT Bureau of Research
QUARTERLY PROGRESS REPORT

Project Title:	A Comparison and Analysis of KA-Band Radar Vs. X-Band Radar			
RFP NUMBER: Project 2007-16	NJDOT RESEARCH PROJECT MANAGER: Edward S. Kondrath			
TASK ORDER NUMBER: 4	PRINCIPAL INVESTIGATOR: Allen Katz			
Project Starting Date: 1/ 1/ 2007 Original Project Ending Date: 12/31/2007 Modified Completion Date:	Period Starting Date: 4/ 1/ 2007 Period Ending Date: 6/30/2007			

Task	% of Total	% of Task this quarter	% of Task to date	% of Total Complete
Literature Search	5%	100%	100%	5%
1. Examine the state of development of Ka-band Radar	10%	20%	90%	9%
2. Prove/disprove Ka-band Radar is as reliable as X-band radar	30%	30%	60%	18%
3. Statistically validate radar testing approaches	25%	40%	60%	15%
4. Develop specifications for Ka- band radar meeting requirements of the Court system	10%	20%	20%	2%
5. Examine the state of development for Laser-band Radar	10%	20%	30%	3%
Final Report	10%	0%	0%	0%
TOTAL	100%			52%

Project Objectives:

1. Examine the state of the art in model development for Ka-band Radar.
2. Prove or disprove that the new technology (Ka-band Radar) is at the least as reliable as the current (X-band radar).
3. Identify data deficiencies and the statistical validity of alternative approaches.
4. Develop specifications and standards for Ka-band radar for all the requirements that are imposed by the Court system to be accepted as an instrument that measures speed.

Added Objectives:

5. Examine the state of the art in model development for Laser-band Radar.

Project Abstract:

This project focuses on the New Jersey State Police commitment to highway safety by enforcing posted speed limits. Effective enforcement of speeding statutes requires measured speed to be accurate and state of the art. This requirement is necessary in order to successfully prosecute by using both moving and stationary radar.

The New Jersey State Police currently utilizes MPH Industries K55 X-band radar units. The New Jersey courts have taken judicial notice as to the scientific reliability of the K55 radar. The advent of new Ka-band Radar technology now allows smaller and safer radar units to be employed. To successfully utilize these new Ka-band Radar units their speed measurement accuracy must be established in a scientific manner that will be accepted by the New Jersey courts.

The purpose of this research project will be to 1) establish a program for testing the performance of the new Ka-band radar units relative to the present K55 radar, 2) monitor the implementation of this testing program, 3) review the test results, 4) provide conclusions on performance and 5) document these conclusions in way the will facilitate the employment of Ka-band radar by the New Jersey State Police.

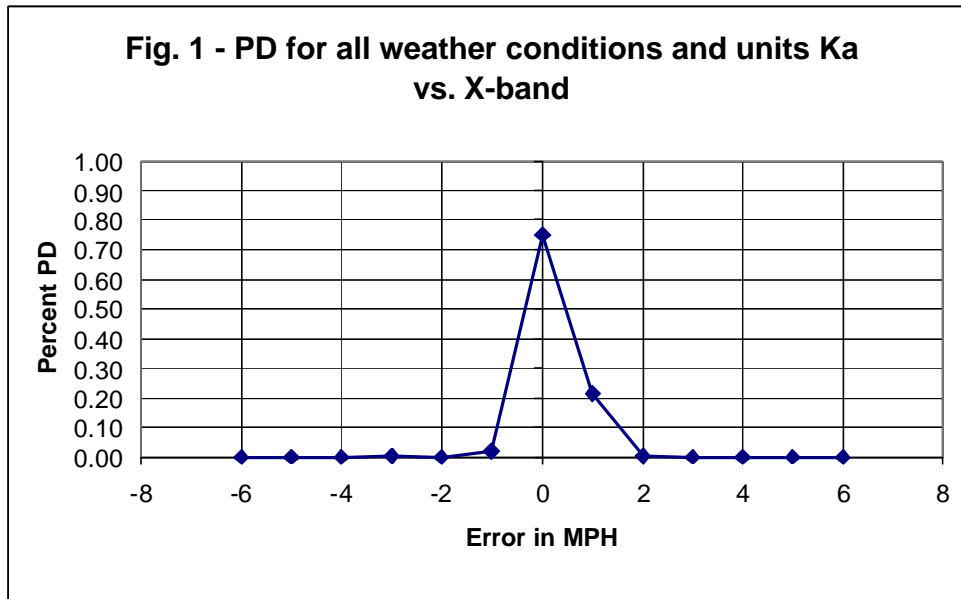
The relative characteristic and performance of available Ka-band radar units will also be investigated and documented.

New and innovative programs like the introduction of the Ka-band radar speed detection devices will enable the Division of State Police to enhance their speed enforcement program to better serve the motorists who travel New Jersey's highways.

1. Progress this quarter by task:

- a) Examine the state of development of Ka-band Radar – A large portion of this task was completed in the first quarter. In this quarter we continued to search the literature for any new developments related to traffic radar. We also met with representatives of Stalker to discuss the operation of their Ka-band radar units. We learned that they are doing more digital signal processing (DSP) than was apparent from their technical literature. This technology is applicable to both their X and Ka-band products. It allows them to differentiate between multiple targets based on spectral analysis of the received vehicular velocities, and should be of significant value in the application of their Ka-band radar units. We were also in contact with MPH and exchanged several e-mails regarding the technology used in their radar units.
- b) Prove/disprove Ka-band Radar is as reliable as X-band radar – We continued to implement the plan for the field testing of Ka-band radar units produced by Stalker and MPH formulated in the first quarter. An additional 400 measurements were made, under varying weather conditions to bring the total number of measurements to 600. Most importantly data was gathered on the performance of the MPH Ka-band radar unit (BEE-III) in comparison to the reference MPH K55 X-band radar unit. Additional data was also taken for the Stalker Ka-band radar unit begun in the first quarter, and the study of the effects of weather on Ka-band vs. X-band Doppler Radar performance continued.

- c) Statistically validate radar testing approaches – The results of the first and second quarter tests were consolidated and statistically analyzed. The results of this analyses are shown in the following figures.



This figure shows the probability density (PD) of the difference between the reference X-band radar unit and the results obtained for both the Stalker and MPH Ka-band radar units under all weather conditions. It can be seen that the agreement is excellent. Radar units are to be accurate within ± 3 mph with virtually no errors greater than 1 mph observed.

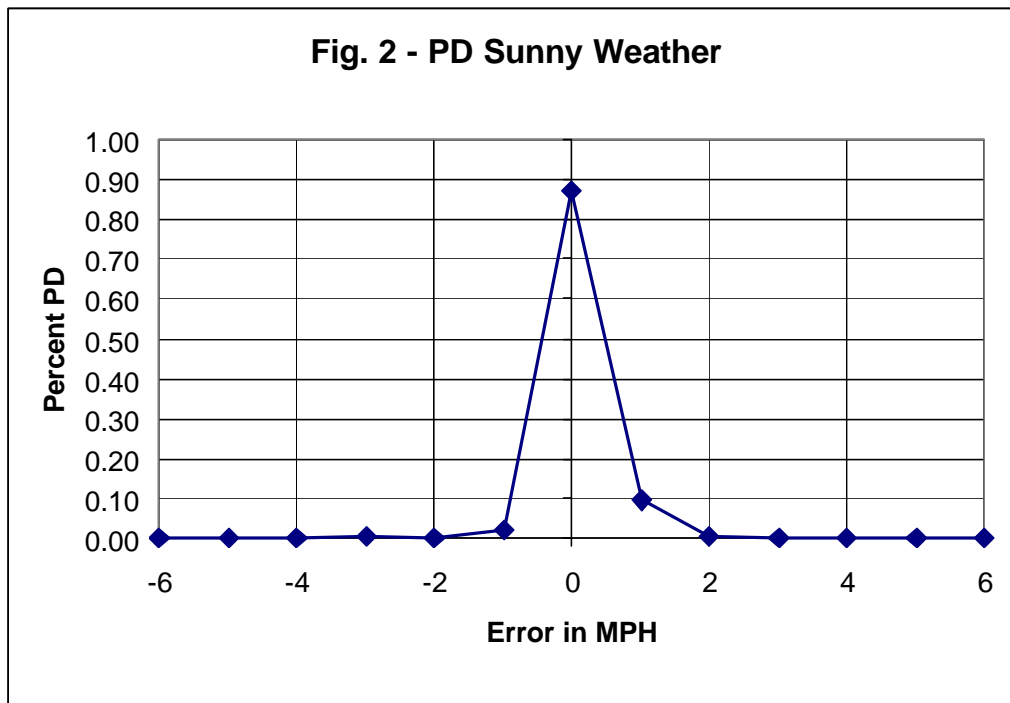


Figure 2 shows the PD for measurement during just fair weather conditions. As might be expected the results are even better than for the all weather conditions. The next graph shows the results for cloudy/wet weather. These results were based on only Stalker Ka-band radar measurements as we do not have bad weather data with the MPH Ka-band unit.

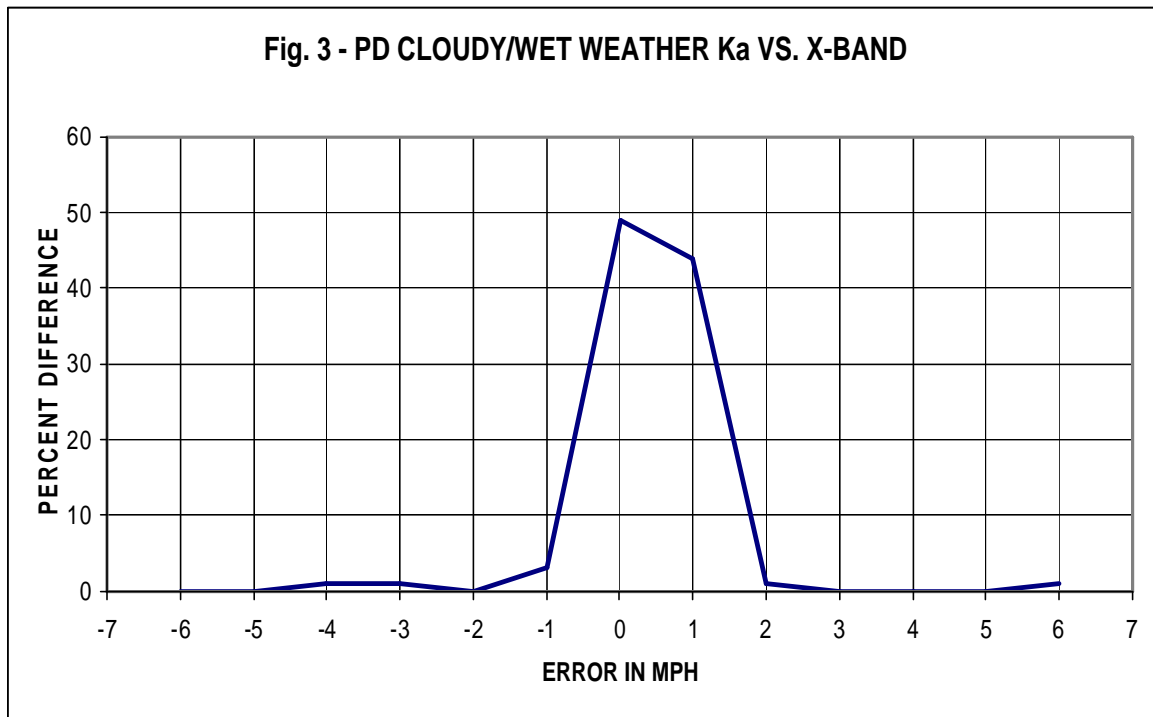
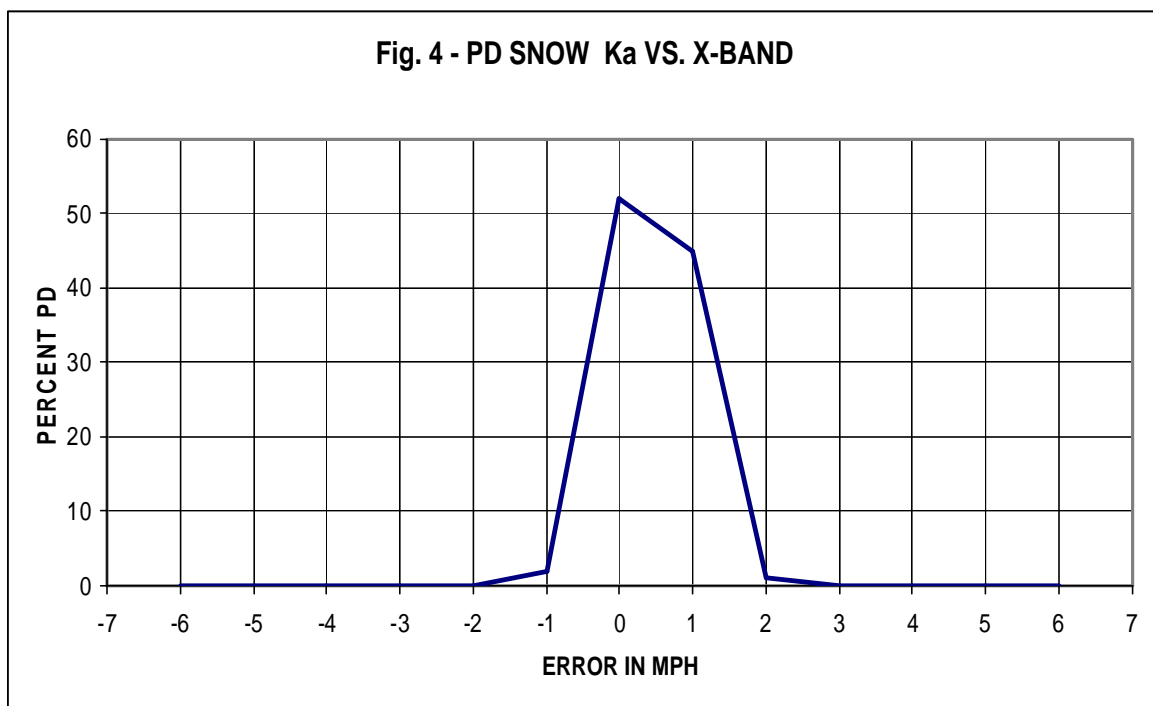


Figure 4. shows the effect of snow on the measurements. These results were again based on only Stalker measurements.



Dr. Guida is reviewing our measurement results under different weather conditions to determine if he can formulate any general conclusions from the data.

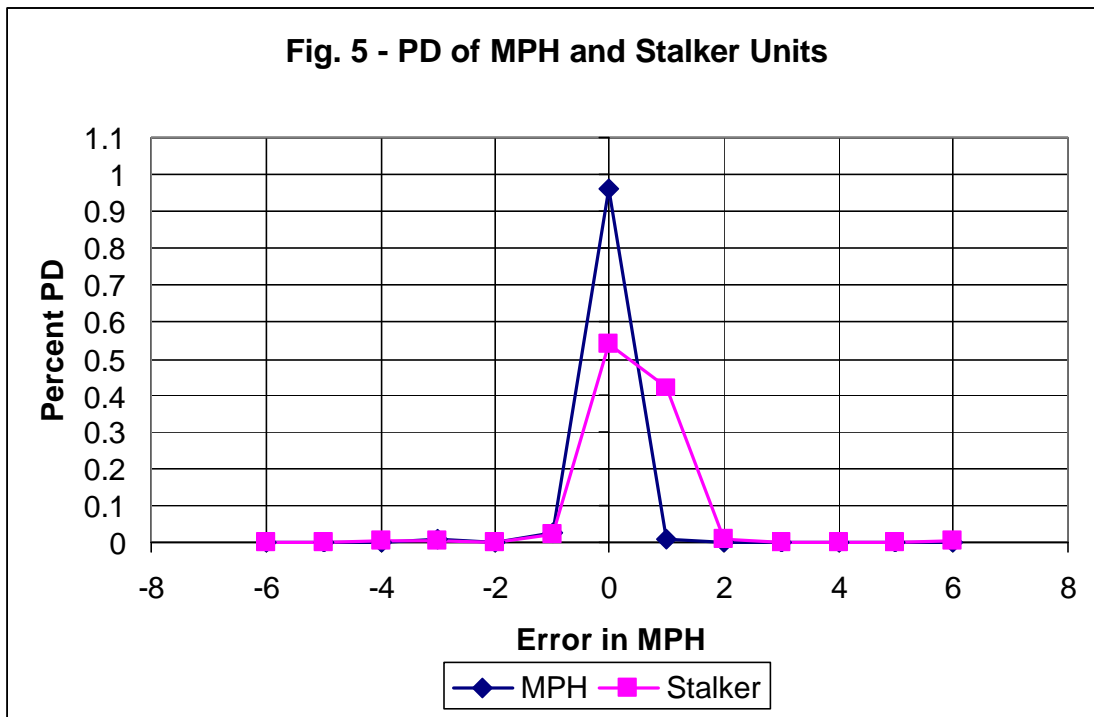


Figure 5 shows a comparison of the measured performance of the Stalker and MPH Ka-band radar units in comparison the X-band K55 reference. Although the errors of the MPH appear smaller, it must be remembered that only fair weather data has been presently taken for the MPH radar. Differences were also observed between the performance of the Stalker and MPH radars when vehicles traveling at low speeds were observed. These results are presently under study and will be discussed in our next report.

Figures 6 and 7 shows the car used for the testing and a picture of the radar equipment used in some of the tests.



Figure 6. Ka-band radar test in progress



Figure 7. Example Ka and X-band radar used during testing

- d) Develop specifications for Ka-band radar that meet the requirements of the Court system – Work has begun on this objective. It is clear from the statistical results that both types of Ka-band radar will more than meet the accuracy requirements imposed by the law. A meeting with the Attorney General's office is planned to determine how to best formulate these requirements.
- e) Examine the state of development for Laser-band Radar – A search of Laser based radar literature has been completed and is attached as an appendix to this report. We have also been in contact some of the manufactures of laser based radar. We had hoped to begin Laser radar testing this quarter, but this task has been delayed and should begin in the next quarter.

2. Proposed activities for next quarter by task

- a) Examine the state of development of Ka-band radar -- This part of the study has been essentially completed. Minimal effort is planned for the next quarter.
- b) Prove/disprove Ka-band Radar is as reliable as X-band radar – Additional measurements will be made on a Stalker Ka-band radar unit relative to an MPH K55 X-band unit. Particularly the evaluation of the MPH Ka-band radar during cloudy/wet weather conditions will be added. The study of the affects of weather on Ka-band vs. X-band Doppler radar performance will be continued.
- c) Statistically validate radar testing approaches – The results of the third quarter tests will be statistically analyzed.
- d) Develop requirements for Ka-band radar meeting requirements of the Court System – Meetings with the Attorney General's office are planned for this quarter.
- e) Examine the state of development for Laser-band radar – The beginning of testing of laser radar systems is anticipated during this quarter.

3. List of deliverables provided in this quarter by task (product date):

- a) Laser Radar Literature Search – Appendix I of this report was completed on 5/31/07.
- b) Second Quarterly Report – was completed on 6/27/07
- c) Monthly reports – It was agreed that meeting minutes would be used in place of monthly reports and were completed on 4/24/07 and 5/04/07 respectively. These minutes are in Appendix II.

4. Progress on Implementation and Training Activities: Not applicable to this project.

5. Problems/Proposed Solutions: None. Desired evaluation of laser radar units was voluntarily accepted as part of this research project.

Total Project Budget	\$49,837.00
Modified Contract Amount:	\$00.00
Total Project Expenditure to date	\$17,704.90
% of Total Project Budget Expended	35.5%

6. Summary:

- Examined the state of development of Ka-band Radar - Contacted representatives of Stalker and MPH to discuss the operation of their Ka-band radar units.
- Data shows Ka-band radar is as reliable as X-band radar – 600 Measurements taken that show Ka-band accuracy within ± 3 mph with virtually no errors > than 1 mph. Additional measurements will be taken in different weather conditions.
- Statistically validated radar testing approach – The results of the first and second quarter tests were consolidated and statistically analyzed.
- Status - Project is on schedule and budget, and proceeding as planned.

7. Appendix I Literature Search

1. Sekine, M., Senoo, T., Morita, I., Endo, H., **Design method for an automotive laser radar system and future prospects for laser radar**, Proceeding of the Intelligent Vehicles '92 Symposium, pp. 120 – 125, June 29, 1992

Summary: Presents a technical explanation of the specific procedure used in designing an automotive laser radar system. Laser radar represents an effective collision avoidance

technology that can contribute to improved vehicle and traffic safety. An analysis is given of the problems involved in the practical application of laser radar and ways of overcoming them. The future prospects for automotive laser radar are also discussed.

2. Verly, J.G., Delanoy, R.L., **Model-based automatic target recognition (ATR) system for forwardlooking groundbased and airborne imaging laser radars (LADAR)**, *Proceedings of the IEEE*, Vol. 84 , pp. 126 – 163, Feb. 1996.

Summary: We describe an experimental, model-based automatic target recognition (ATR) system, called XTRS, for recognizing tactical vehicles in real or synthetic **laser-radar** (LADAR) range and intensity images corresponding to a forwardlooking, CO₂ **laser radar** (LADAR) that is carried either on a ground vehicle or on an airborne platform. Various aspects of the system's operation are illustrated through a variety of examples. Generic techniques are highlighted whenever possible. A first such technique is the use of feature-indicating interest images to focus attention on specific areas of the input imagery. A second is the use of an application-independent matching engine for matching features extracted from the imagery against an application-dependent appearance model hierarchy that represents the objects to be recognized. A third generic technique is the system's architectures and its control mechanism. Following the description of XTRS, we discuss XTRS's recognition performance on real data collected with the groundbased version of the ladar sensor. We then provide a detailed account of XTRS's performance on synthetic datasets created to test the limits of system performance. Finally, we briefly discuss the use of XTRS in conjunction with the airborne version of the sensor. Overall, more than 1500 range and intensity image pairs were used throughout XTRS's development

3. Vaughan, J.M., Steinvall, K.O., Werner, C., Flamant, P.H., **Coherent laser radar in Europe** *Proceedings of the IEEE*, Vol. 84 , pp. 205 – 226, Feb. 1996.

Summary: European work in coherent **laser radar** with 10 μm and shorter wavelength **lasers** is reviewed. Fundamental aspects include heterodyne studies of signal statistics and fluctuations, and detailed experimental and theoretical work on signal amplification and autodyne arrangements with light reinjected into the **laser** cavity. Progress with **lasers**, detectors, and modulators has led to the development of several compact robust field systems both continuous-wave and pulsed. Various ground-based programs are described including local wind field measurement and wake vortex investigation at airfields, and study of range, image, and Doppler shift of hard targets. Airborne systems have investigated avionics problems of true airspeed, pressure error, and wind shear warning. Other airborne studies include ground imaging, obstacle warning, terrain following, and a compendium of atmospheric backscattering over the North and South Atlantic. In recent years, the European Space Agency has supported studies and technology development for a space-borne wind lidar in the Atmospheric **Laser** Doppler Instrument (ALADIN) program.

4. Gronwall, C., Carlsson, T., Gustafsson, F., **Performance analysis of measurement error regression in direct-detection laser radar imaging**, *Proceedings Acoustics, Speech, and Signal Processing*, Vol 6, pp. 545-548, April 2003.

Summary: In this paper a tool for synthetic generation of scanning laser radar data is described and its performance is evaluated. By analyzing data from the system, we recognize objects on the ground. In the measurement system it is possible to add several design parameters, which make it possible to test an estimation scheme under different types of system design. The measurement system model includes **laser** characteristics, object geometry, reflection, speckles, atmospheric attenuation, turbulence and a direct detection receiver. A parametric method that estimates an object's size and orientation is described. There are measurement errors present and thus, the parameter estimation is based on a measurement error model. The parameter estimation accuracy is limited by the Cramer-Rao lower bound. Validations of both the measurement error model and the measurement system are shown. Data from both models generate parameter estimates that are close to the Cramer-Rao lower bound.

5. An-Ping Wang, Jie-Cheng Chen, Pao-Lo Hsu, Intelligent CAN-based automotive collision avoidance warning system, Networking, Sensing and Control, 2004 IEEE International Conference Digest, Vol. 1, pp. 146-151, March 21-23, 2004.

Summary: To construct a vehicle collision avoidance system, a laser radar and three ultrasonic sensors are integrated with the CAN bus to build the in-car network architecture to prevent the car on all directions. There are two sub-systems developed for this collision avoidance system: (a) the front-end sub-system and (b) the side and rear-end sub-system. The front-end collision warning sub-system is constructed for high-speed driving conditions by measuring the distance in the front with a laser radar. Moreover, the relative speed between two cars can be properly estimated by applying the current Kalman filter. Then, a D/V curve is further obtained to generate collision warning with a desirable precaution time to prevent the front-end collision actively. For the collision avoidance on the side and the rear-end, the approaching speed from other cars in general is slow and available ultrasonic sensors with limited range and resolution are adopted. An intelligent approach is proposed to process the rough distance readout to render warning signals with suitable timing for the approaching car drivers to prevent the collision passively. A high-level network protocol CANopen is applied to integrate all ultrasonic sensors as the in-car network communication.

6. Buhren, Markus, Yang, Bin, **A Global Motion Model for Target Tracking in Automotive Applications**, Acoustics, Speech and Signal Processing, Vol. 2, pp. 113-115, April 15-20, 2007.

Summary: In common automotive radar tracking systems, simple linear models are used to track targets separately in longitudinal and angular direction relative to the own vehicle (or sensor) position. Under the special condition that the observed targets are straight ahead and moving nearly in the same direction as the observing vehicle, like in adaptive cruise control (ACC) systems, those models work well. In more general scenarios, where movements of other vehicles have to be tracked in all possible directions and all around the vehicle (e.g. in inner-city or intersection situations), the modeling is insufficient. In this paper we review the drawbacks of the commonly used models and present a more general motion model for automotive tracking systems. All necessary expressions for an implementation using an extended or unscented Kalman filter are given. Even if designed for radar systems, the state model is not limited to a special type of sensor. It can be used for ultrasonic or laser scanner systems as well as for vision-based systems with a different measurement model.

7. Chiricescu, S., Chai, S., Moat, K., Lucas, B., May, P., Norm, J., Essick, R., Schuette, M., **RSVP II: a next generation automotive vector processor**, Intelligent Vehicles Symposium, pp. 563-568, June 6-8, 2005.

Summary: A large number of sensors (i.e., video, radar, laser, ultrasound, etc.) that continuously monitor the environment are finding their way in the average automobile. The algorithms processing the data captured by these sensors are streaming in nature and require a high rate of computation. Due to the characteristics of the automotive environment, this computation has to be delivered under very low energy and cost budgets. The reconfigurable streaming vector processing (RSVP/spl trade/) architecture is a vector coprocessor architecture which accelerates streaming data processing. This paper presents the RSVP architecture and its second implementation, RSVP II. Our results show significant speedups on data streaming functions running compiled code. On a lane tracking application, RSVP II shows impressive performance results. From a performance/\$ and performance/mW perspective, RSVP architecture compares favorably with leading DSP architectures. The time to market is substantially reduced due to ease of programmability, elimination of hand-tuned assembly code, and support for software re-use through binary compatibility across multiple implementations.

8. Neri, C., Baccarelli, G., Bertazzoni, S., Pollastrone, F., Salmeri, M., **Parallel hardware implementation of radar electronics equipment for a laser inspection system**, Nuclear Science Symposium Conference Record, Vol. 3. Vol. 3, pp. 1352-1356, Oct. 16-22, 2004.

Summary: An amplitude modulated laser radar has been developed by ENEA (Italian Agency for new technologies, energy and environment) for periodic in-vessel inspection in large fusion machines (ITER). The system is able to obtain a complete 3D mapping of the in-vessel surface. First, a digital signal processing system was developed to modulate the laser beam and to detect both the amplitude of the back scattered light and the phase difference between it and the modulation signal. This system is based on commercial digital receiver and parallel DSP (digital signal processing) boards on a VME bus. It reaches a speed of 100 K measures/s showing good accuracy and stability. Starting from this, further development has been done to increase the speed up to 2.328 M measures/s. To reach the sub-microsecond speed it was necessary to implement the mathematical algorithm in a highly parallel hardware architecture using FPGAs (field programmable gate array). Looking at the good results of previously developed system it was decided to maintain the same acquisition front-end. The last release of A/D converters was used to increase the operating frequency up to 200 MHz, but the previously used software algorithm was completely redesigned and optimized to be used in the FPGA hardware architecture.

9. Hancock, J., Langer, D., Hebert, M., Sullivan, R., Ingimarson, D., Hoffman, E., Mettenleiter, M., Froehlich, C. **Active laser radar for high-performance measurements**, Proceedings of Robotics and Automation, 1998. Vol. 2, pp. 1465 – 1470, May 16-20, 1998.

Summary: Laser scanners, or laser radars (ladar), have been used for a number of years for mobile robot navigation and inspection tasks. Although previous scanners were sufficient for low speed applications, they often did not have the range or angular resolution necessary for

mapping at the long distances. Many also did not provide an ample field of view with high accuracy and high precision. In this paper we will present the development of state-of-the-art, high speed, high accuracy, 3D laser radar technology. This work has been a joint effort between CMU and K2T and Z+F. The scanner mechanism provides an unobstructed 360° horizontal field of view, and a 70° vertical field of view. Resolution of the scanner is variable with a maximum resolution of approximately 0.06 degrees per pixel in both azimuth and elevation. The laser is amplitude-modulated, continuous-wave with an ambiguity interval of 52 m, a range resolution of 1.6 mm, and a maximum pixel rate of 625 kHz. This paper will focus on the design and performance of the laser radar and will discuss several potential applications for the technology. It reports on performance data of the system including noise, drift over time, precision, and accuracy with measurements. Influences of ambient light, surface material of the target and ambient temperature for range accuracy are discussed. Example data of applications will be shown and improvements will also be discussed.

10. Meng Lu, Wevers, K., van der Heijden, R., Heijer, T., **ADAS applications for improving traffic safety**, Systems, Man and Cybernetics, Vol. 4, pp. 3995-4002, Oct. 10-13, 2004.

Summary: Governments in several European countries, and the EU have set challenging targets for the improvement of road traffic safety by the year 2010. In the Netherlands a program for infrastructure measures was launched, to meet the Dutch targets. The ongoing developments in the field of ITS applications seem however to offer viable alternatives for large-scale infrastructure reconstruction. This paper explores the feasibility of five ADAS applications (navigation, speed assistance, collision avoidance, intersection support and lane keeping) to complement or partly substitute infrastructure measures to reach the stated goals. State-of-the-art and the potential of enabling technologies like positioning, radar, laser, video imaging and communication are analysed from a technical perspective. Technical issues relating to large-scale dedicated ADAS implementation for traffic safety, as well as related policy issues are discussed.

11. Fisher, P.D., Pyhtila, J.W., **Timing quantization error in lidar speed-measurement devices**, IEEE Transactions on Vehicular Technology, Vol. 49, pp. 276-280, Jan. 2000.

Summary: Minimizing the timing quantization error of lidar speed-measurement devices is an important step in reducing the magnitude of the speed-measurement errors associated with these devices. This paper presents a statistical model for the timing quantization error and demonstrates how this model can be used to select the values of key timing parameters. The values of these parameters must be carefully selected so that manufactured equipment meets current model lidar speed-measurement device performance standards established by the National Highway Traffic Safety Administration (NHTSA).

12. Kawashima, S., Watanabe, K., Kobayashi, K., Traffic condition monitoring by laser radar for advanced safety driving, Proceeding of the Intelligent Vehicles '95 Symposium, pp. 200-303, Sept. 25-26, 1995.

Summary: This paper describes the accurate and detailed estimation of traffic conditions around our vehicle on road by the incomplete laser radar signals. The conventional laser radar system monitors only one vehicle that runs just in front of the our vehicle. Careful observation of the laser radar signals includes more information than that required. This research aims at developing a new traffic condition monitoring system that monitors 8 to 10 vehicles that run around our vehicle by fully using the signals from the radar

8. Appendix II Meeting Minutes

Ka-band Radar Research Meeting Minutes April 24, 2007

Present: Sgt. Greg Williams, NJ State Police and Dr. Allen Katz, TCNJ

This meeting was held by teleconference. Due to a very busy schedule and conflicting activities, it was not convenient to have a meeting in person. Rather than delay the meeting further it was decided to have it via telephone.

1. Trooper Williams reported that despite conflicting activities, he was able to complete 100 measurements comparing the performance of the present X-band radar unit to a MPH Ka-band radar unit. All of these measurements were made in fair weather. He plans to take additional measurements,
2. Dr. Allen Katz reported that he had completed a library search of articles relating to laser radar.
3. He also reported that he had identified a student who could assist Trooper Williams with his testing.
4. The need to also begin laser radar testing was also discussed.
5. A date for the next meeting was not set. Trooper Williams will contact Dr. Katz to set a date.

Ka-band Radar Research Meeting Minutes May 4, 2007

Present: Sgt. Greg Williams, NJ State Police, Dr. Allen Katz, TCNJ, Dr. Allan Guida, LTI, and Joe Heitmann, TCNJ student

1. Sgt. Williams reported on the results of testing of the MPH Ka-band radar unit in comparison to the current X-band K55 units. All measurements were made in fair weather. He reported that the MPH radar appeared to have less divergence than the Stalker unit previously tested, but both were well within specification.
2. Dr. Allen Katz received 200 data points and reported that he would analyze the measurements statistically and prepare a graphical presentation – [see ANAL052807].

3. The pros and cons of both units were discussed. The Stalker unit provides simultaneous display of both forward and back-looking radar returns. This feature is not offered by the MPH radar.

4. Joe Heitmann was introduced and his availability to assist with the measurements discussed.

5. Sgt. Williams supplied pictures of the testing that could be used in future reports. He also explained that because of unexpected complications at State Police Headquarters, he was unable to start the laser radar testing. He expects to be able to begin soon.

6. Open AIs were reviewed. The meeting with the Attorney General's Office has not yet been scheduled.

7. A date for the next meeting was not set, but it will probably be in mid June after Dr. Katz returns from the International Microwave Symposium.